EXPERIMENTAL AND NUMERICAL STUDY OF IRREGULAR WAVE BOUNDARY LAYERS ON A ROUGH BOTTOM

AHMAD SANA

Department of Civil and Architectural Engrg., Sultan Qaboos University, PO Box 33 Muscat 123,, Sultanate of Oman

HITOSHI TANAKA

Department of Civil Engineering, Tohoku University, 06 Aoba Sendai 980-8579, Japan

TAKESHI SUZUKI

Civil Engineer, Tohoku Electric Power Co. Inc., 3-7-1 Ichibancho, Aoba Sendai 980-8550, Japan

An experimental and numerical study has been conducted to investigate the properties of irregular wave boundary layers on a rough bottom. Detailed measurement of velocity profiles was done using 1D Laser Doppler Anemometer. It was observed that the turbulence might persist under a free-stream Reynolds numbers within laminar range. The original version of $k-\omega$ model and two versions of two-layer $k-\omega$ models have been used to predict the boundary layer properties under experimental conditions. It was found that the model could reproduce the shear stress variation in time quite successfully but the magnitude could not be predicted adequately. This discrepancy may partly be due to the estimation of the shear stress from the velocity data by log-law.

1. Introduction

In the past most of the studies related to oscillatory boundary layers dealt with the regular waves, that is, sinusoidal wave boundary layers. Those studies provided valuable fundamental knowledge about turbulent characteristics of the bottom boundary layers. Thus improving our understanding of sediment transport phenomena (Sleath, 1990). However, in a real field situation, the waves are essentially irregular. The irregularity of the waves affects the dynamic properties of the bottom boundary layers and in turn sediment transport in the field. Thus, there is a need for comprehensive experimental and numerical studies in order to enhance the level of understanding of irregular wave boundary layers.

Simons et al.(1994) reported some experimental results for irregular wave bottom boundary layers. Recently, Samad et al. (2001) conducted experiments on irregular wave boundary layers on smooth bottom. They measured the velocity by 1D LDA and calculated shear stress using the log-law.

A number of analytical models have been developed to study the irregular wave boundary layer properties (Madsen et al., 1988, Myrhaug, 1995). Numerical models have also been used in this regard. For sinusoidal oscillatory boundary layers two-equation turbulence models have been utilized by a number of researchers. For practical purposes, two equation models have been very successful in predicting the mean and fluctuating parameters of oscillatory boundary layers on smooth bottoms (Sana and Tanaka, 2000, Sana and Shuy, 2002) and rough boundaries (Sajjadi and Waywell, 1997). For irregular wave boundary layers on a smooth bottom Samad and Tanaka (1999) used a low Reynolds number k-ε model and predicted the bottom shear stress in order to propose an estimation method of shear stress under irregular waves. Holmedal et al.(2003) used the standard version of k-ε model to study the boundary layer properties under irregular waves plus current.

In the present study, the experiments have been conducted under irregular oscillatory motion on a rough bottom. For numerical prediction the two-layer k-ω model developed by Menter(1994) has been used. This model was developed by utilizing k-ω model in the near-wall region and k-ε model far from the wall due to relatively better predictive capabilities of both the models in the respective regions. The benefit in using a k-ω model over k-ε model is that in the former model the value of ω can directly be specified in terms of the equivalent sand grain roughness on a rough surface, whereas in k-ε model, wall functions are commonly used to specify the surface roughness (Justesen, 1988). Unlike steady flows, the use wall function method for oscillatory boundary layers is debatable due to dynamic properties of turbulence characteristics. Patel and Yoon(1995) compared the results of k-ω model proposed by Wilcox(1988) and a two-layer k-ε model for turbulence under separated flow and found the former model performing much better than the latter one. Two-layer models proposed by Menter have been used for an oscillatory wave boundary layer and good agreement has been found with DNS data (Sana and Shuy, 2002).

2. Experimental Study

The experiments were carried out in an oscillating tunnel using air as the working fluid. The triangular elements, similar to those used by Jonsson (1966), were pasted on the bottom surface as roughness. The oscillatory motion was generated by a computer-controlled mechanism. The description of the whole experimental system is given by Samad et al.(2001). The velocity was measured

by fiber optic LDV and the bottom shear stress was calculated assuming logarithmic velocity profile near the bottom.
A random signal was generated using Bretschneider-Mistuyasu spectral density formulation. A part of the signal was then used as input to the piston mechanism and the experimental data for velocity was obtained for a minimum of 50 cycles of the input signal. The data analysis was carried out using PC. Table 1 shows the experimental conditions used in the present study.

Table 1. Experimental Conditions

Exp	$T_{1/3}$ (s)	$U_{1/3}$ (cm/s)	ν (cm^2/s)	RE	S	K_s/y_h
1	3.0	393.7	0.148	500,000	16.8	0.657
2	3.0	470.0	0.144	730,000	20.1	0.657

Where, $T_{1/3}$ and $U_{1/3}$ are significant wave period and significant free-stream velocity, respectively, ν: kinematic wave height, K_s: Nikuradse's equivalent roughness height, y_h: distance from the bottom to axis of symmetry of the tunnel, RE: $(=U_{1/3}^2 T_{1/3}/2\pi\nu)$ Reynolds number and S: $(=U_{1/3}T_{1/3}/2\pi y_h)$ reciprocal of Strouhal number. Figure 1 shows the mean velocity and pressure gradient at the axis of symmetry of the measurement section in the wind tunnel. This pressure gradient was calculated from the experimental data of mean velocity and then used as the boundary condition for the numerical models. The simulated free-stream velocity from the model is also shown.

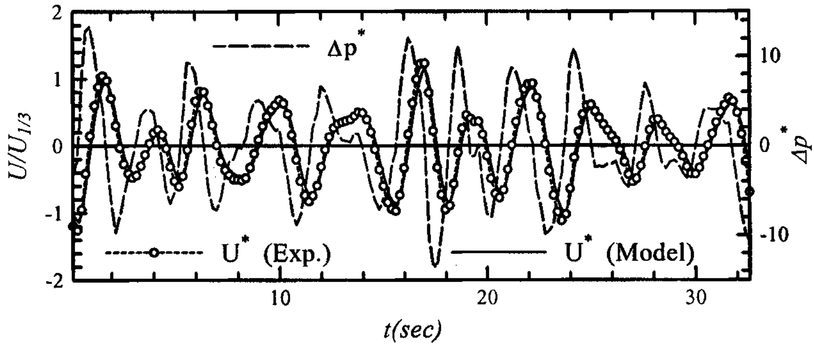

Figure 1. Dimensionless mean velocity and pressure gradient at the axis of symmetry of the tunnel.

3. Numerical Model

Governing equations comprise of two-layer $k-\omega$ model proposed by Menter(1994). The effect of roughness was considered using Wilcox(1988) approach to specify the wall value of ω in terms of Nikuradse's roughness height. The governing equations were normalized by using significant free-stream velocity, significant angular frequency($2\pi / T_{1/3}$), kinematic viscosity and y_h. The detail about the equations and the numerical procedure is shown by Sana and Tanaka(2001). In the present study we used three types of two-layer $k-\omega$ models proposed by Menter(1994), namely Wilcox (WL), Baseline (BSL) and Shear Stress Transport (SST) model. A detailed description of the governing equations for smooth boundaries may be seen in Menter (1994) or Sana and Shuy (2002). In the present study the effect of roughness was introduced through the wall boundary condition of ω after Wilcox(1988).

At the wall, no slip boundary condition for the velocity and turbulent kinetic energy is used, i.e. at $y=0$ $u=k=0$, and at the axis of symmetry of the oscillating tunnel, the gradients of velocity, turbulent kinetic energy and specific dissipation rate were equated to zero, i.e. at $y=y_h$ $\partial u / \partial y = \partial k / \partial y = \partial \omega / \partial y = 0$.

The wall boundary condition for ω is given as (Wilcox, 1988):

$$\omega_o = \frac{u_f^2 S_R}{\nu} \tag{1}$$

Where $u_f = \sqrt{\tau_o / \rho}$ (friction velocity) and function S_R is expressed as: $S_R = (50/k_s^+)^2$ for $k_s^+ \le 25$ and $S_R = 100/k_s^+$ for $k_s^+ > 25$ where $k_s^+ = u_f k_s / \nu$.

A Crank-Nicolson type implicit finite difference scheme was used to solve the governing equations for the three models. The grid spacing was allowed to vary exponentially in the cross-stream direction to get fine resolution near the wall. In space 100 and in time 9960 steps were used. The convergence was achieved in two stages; at the first stage the convergence was based on the dimensionless values of u, k and ω at every time instant during a wave cycle. The second stage convergence was based on the maximum wall shear stress value. The convergence limit was set to 1×10^{-6} for both the stages. It was observed that a number of wave cycles were required to meet the convergence criterion.

4. Results

In another study Sana et al.(2004) have utilized the experimental data of Case 12 by Jensen(1989) for predictive ability of the models under consideration. It is shown that the velocity, turbulent kinetic energy, Reynolds stress and wall shear stress are satisfactorily predicted by three of the model versions considered here. However, it must be noted here that the relative roughness in the present study is 0.657 whereas in Jensen's Case 12, it is 0.0058. Moreover, in the present study two-dimensional roughness elements are used whereas, Jensen used 3D roughness in the form of sand grains.

Figure 2 shows the wall shear stress data along-with the model predictions. All the three versions satisfactorily show the variation of wall shear stress and able to capture rather fine details of the secondary peaks. But all the peak values of the shear stress, except the highest one, are underestimated. The prediction by WL model and BSL model are similar and these models perform better than SST model especially at higher peaks. In order to further investigate the underestimation of peak shear stress, the velocity profiles at three selected instants (t =9.7, 13.2 and 21.8 sec) are shown in Figure 3 in comparison with SST model prediction.

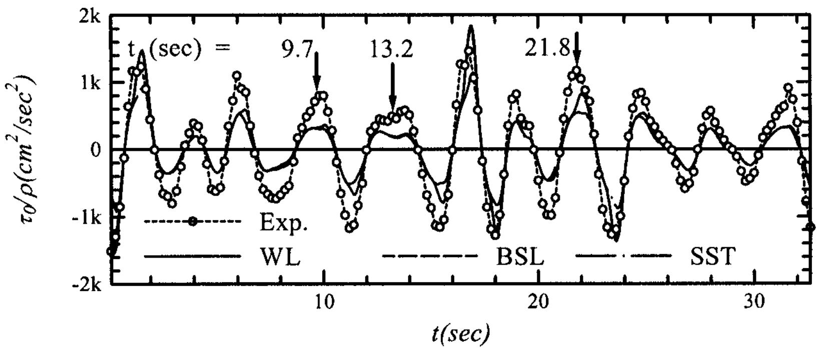

Figure 2. Wall shear stress prediction by the three versions of k-ω model for Case 1.

It may be observed that SST model underestimates the wave boundary layer thickness at the instants shown in Figure 3. The model, however, depicts turbulent characteristics by showing small amount of overshooting in accordance with the experimental data. The experimental data show a well-defined log-law region at t =9.7sec and t = 13.2 sec, but the numerical model does not simulate this behavior.

In order to further elaborate the predictive abilities of the models, Figure 4 shows the dimensionless wall shear stress. The model predictions are plotted versus the experimental data. The solid line shows the line of perfect agreement. It is evident that WL model and BSL model predict higher values of the shear stress satisfactorily, whereas the performance of SST model is poorer as compared to the former models. This discrepancy may be due to a very high roughness used in the present experiment; where the isotropic nature of turbulence does not exist near the wall. In Jensen's experiment, the wall roughness three-dimensional and has very small magnitude, therefore, the model could somehow predict the wall shear stress satisfactorily.

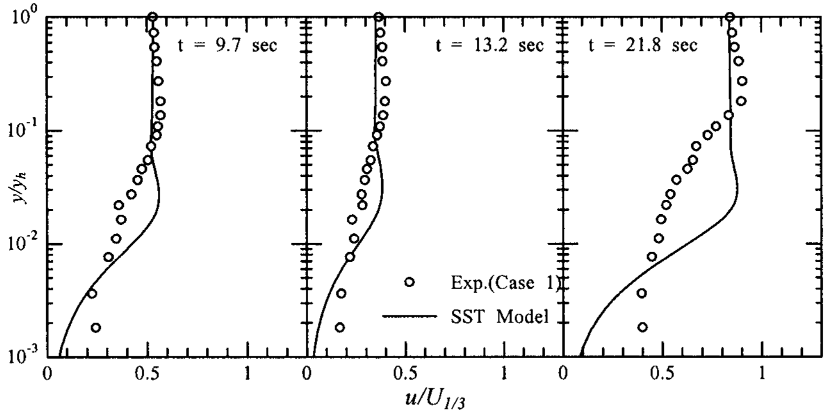

Figure 3. Velocity profiles under three selected peaks of wall shear stress.

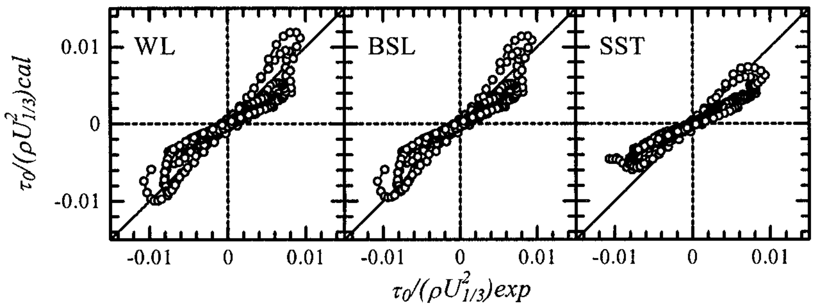

Figure 4. Overall comparison for the wall shear stress between experimental data and model predictions for Case 1.

5. Conclusions

A set of experiments was carried out under irregular oscillations in a wind tunnel. The velocity measurement was done using 1D LDA and the wall shear stress was calculated using log-law. Three versions of $k-\omega$ model were used to predict the boundary layer properties. As a result of the present study, it may be concluded that the present experimental system can be effectively used for further investigations under irregular oscillations. The numerical models used in the present study may perform well for small relative roughness values as shown by Sana et al. (2004), but for very high roughness as in the present case, the wall shear stress is underestimated due to poor prediction of the velocity profiles. However, the variation of the shear stress was predicted satisfactorily by three of the models. Further studies are needed to investigate other types of numerical models in order to predict the boundary layer properties under irregular waves. This research is useful for the selection of a suitable model for bottom shear stress prediction and in turn the estimation of sediment transport in coastal environments.

Acknowledgments

A part of this study was completed when the first author was on leave from Sultan Qaboos University, Oman to work at Tohoku University, Japan as a JSPS fellow during Summer 2003. The first author is thankful to the above organizations for their support.

References

Holmedal, L.E., Myrhaug, D. and Rue, H., 2003, The sea bed boundary layer under random waves plus current, *Continental Shelf Research*, Vol. 23, 717-750.

Jensen, B. L. 1989. *Experimental Investigation of Turbulent Oscillatory Boundary Layers*, Series Paper No.45, ISVA, Technical Univ. of Denmark.

Jonsson, I.G., 1966, Wave boundary layers and wave friction factors, *Proc. 10th Int. Conf. Coastal Engineering*, pp. 127-148.

Justesen, P. 1988. *Turbulent Wave Boundary Layers*, Series Paper No.43, ISVA, Technical Univ. of Denmark.

Madsen, O.S., Poon, Y.K. and Graber, H.C., 1988, Spectral wave attenuation by bottom friction: Theory, *Proc. 21st Int. Conf. Coastal Engineering*, pp. 492-504.

Menter, F. R. 1994 Two-Equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, Vol. 32, No. 8, 1598-1605.

Myrhaug, D., 1995, Bottom friction beneath random waves, *Coastal Engineering*, Vol. 24, 259-273.

Patel, V.C. and Yoon, J.Y., 1995, Applications of turbulence models to separated flow over rough surfaces, *J. Fluids Engineering, ASME*, Vol. 117, 234-241.

Sajjadi, S. G. and Waywell, M. N. 1997. Application of roughness-dependent boundary conditions to turbulent oscillatory flows, *Int. J. Heat and Fluid Flow*, Vol. 18, 368-375.

Samad, M.A. and Tanaka, H., 1999, Estimating instantaneous turbulent bottom shear stress under irregular waves, *J. Hydroscience and Hydraulic Engineering*, Vol. 17, No. 2, 107-126.

Samad, M.A., Tanaka, H. and Yamaji, H., 2001, Flow transitional behavior in smooth bed bottom boundary layer beneath irregular oscillatory motions, *J. Hydroscience and Hydraulic Engineering*, Vol. 19, No. 1, 117-130.

Sana, A. and Shuy, E. B. 2002. Two-equation turbulence models for smooth oscillatory boundary layers, *J. Waterway, Port, Coastal and Ocean Eng., ASCE*, Vol. 128, 38-45.

Sana, A. and Tanaka, H. 2000. Review of $k-\varepsilon$ model to analyze oscillatory boundary layers. *J. Hydraul. Eng.*, ASCE, Vol. 126, No.9, 701-710.

Sana, A., Ghumman, A.R., Tanaka, H. and Shamim, M. A., 2004, Numerical modeling of rough oscillatory boundary layers using two-equation turbulence models, *Journal of Hydraulic Research*, IAHR, (submitted).

Simon, R.R., Grass, T.J., Saleh W.M. and Tehrani, M.M. 1994, Bottom shear stress under random waves with a current superimposed, *Proc. 24th Int. Conf. Coastal Engineering*, Vol. 1, pp. 565-578.

Sleath, J. F. A. 1990, Seabed boundary layers. In *The Sea*, Vol. 9B, 693-727.

Wilcox, D.C. 1988. Reassessment of the scale-determining equation for advanced turbulence models, *AIAA Journal*, Vol.~26, No.11, 1299-1310.